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February 12, 1993

Ms. Donna R. Searcy
Secretary
Federal Communications Commission
Room 222
1919 M Street, N.W.
Washington, D.C. 20554

Re: <u>ET Docket 92-100</u>

Dear Ms. Searcy:

On January 11, 1993, representatives of SpectraLink Corporation, Ericsson Corporation, Motorola, Inc., Northern Telecom., AT&T, and Rose Communications, Inc., met with Mr. Bruce A. Franca, Deputy Chief Engineer and several members of the staff of the Office of Engineering and Technology and discussed several issues concerning the Commission's proposal in ET Docket 92-100 to allocate a portion of the radio spectrum in the 2 GHz band for "unlicensed" devices to be used for certain personal communications services.

The matters discussed during that meeting are described in the attached document titled "<u>Spectrum Requirements for Unlicensed Wireless Voice Services</u>." Two copies of that document are enclosed. Please associate them with the Commission's files for ET Docket 92-100.

Respectfully submitted,

FLETCHER, HEALD & HILDRETH

George Petrutsas
Counsel for Spectralink Corporation

GP:cej
Enclosures
cc: Mr. Bruce A. Franca (w/enc.)(VIA HAND DELIVERY)
    Mr. Richard Engleman (w/enc.)(VIA HAND DELIVERY)
    Mr. Fred Thomas (w/enc.)(VIA HAND DELIVERY)
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Spectrum Requirements for
Unlicensed Wireless Voice Services

FEB 12 1993

Presented by the Contributing Members
of the WINTech Voice Sub-Committee
to WINTech, on January 27, 1993

FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF THE SECRETARY

Wireless PBX systems are among the applications intended for the unlicensed portion of the proposed PCS frequency allocation. This report analyses the spectrum requirements for such a system and includes factors based on both reality and forethought.

The analysis derives a range for the required spectrum from a consideration of a number of factors which enter into the computations:

1. System Description
    - includes architecture, basic assumptions

2. Traffic analysis
    - includes user density, blocking factors, etc.

3. Audio bit rate requirements per conversation
    - includes summary of applicable compression methods

4. System bit overhead requirements and modulation formats
    - includes data points from existing accepted systems

5. Propagation issues and frequency reuse

For some parameters a range of values is obtained for increased generality, and for others a nominal value is selected for simplicity of perspective.

System Description

A suitable in-building wireless PBX system benefits from a micro-cellular design which maximizes traffic-handling capability over a large geographic area. By employing a micro-cellular architecture, the system can take advantage of frequency reuse to occupy the available frequency spectrum as efficiently as possible.

A micro-cellular design is desirable for several reasons:

1) A wireless user can make or take a call from any location, without having to remain within a "home" area, thus increasing the usefulness of the wireless system.

2) A wireless user is free to "roam" about the facility, while engaged in a telephone call, allowing the user to have unprecedented freedom to communicate.

3) Microcells can provide system coverage in areas where service is specifically required, thus improving spectral utilization. This prevents spectrum from being used inefficiently in areas where coverage is unnecessary.

4) A micro-cellular design can share spectrum with neighboring systems, in a manner which minimizes mutual interference and maximizes access to the spectrum.

Therefore, the model for an in-building wireless PBX system assumes the following basic components:

1) A radio or base station controller, which resides near or adjacent to the wired PBX system. This controller acts as the gateway between the PBX system and the rest of the wireless system, serving as the mechanism which forwards calls from the PBX to the handset of the user.

2) A base station which is connected to the controller via dedicated wiring creates a microcell of coverage. Each microcell provides an area of coverage for wireless access to the system. A microcell can serve as few as one user, or as many as the system design will allow. Typically microcells range from serving two to twelve simultaneous users. A number of base stations are connected to the controller in an arrangement which provides ubiquitous microcellular coverage over the user's facility, and system software allows a call in progress to be "handed-off" between microcells.

3) The handset provides user access to the wireless PBX system. The handset becomes a wireless version of the user's deskset, allowing the user to make or take telephone calls while away from the desk. Ideally, the handset operates with the system in such a manner that the user is not expected to be aware of the location of individual microcells.

Traffic Analysis

This section recommends a minimum amount of channels necessary for a single cell offering a grade of service comparable to a wired PBX alternative.

1) User density, consisting of primary office space and including the allocation of hallway space, copier/fax machine areas, meeting rooms, common areas but excluding cafeterias and lunchrooms, is determined to be between 150 to 225 square feet per employee, with an average value of 185 square feet per employee.

2) For in-building applications, the goal of any wireless manufacturer is 100% utilization. While the average initial utilization may be on the order of 25%, some customers may require 100% utilization from the outset to accommodate specific departments or facilities requiring wireless communications.

3) The realistic power output of a microcellular base station and its corresponding handset ranges from 31 mW for a 100 kHz FDMA system to 112 mW for a 1.25 MHz TDMA system. Empirically, this provides "adequate" radio link performance in the range of 50 to 75 feet, with building construction materials and technologies accounting for the spread. "Adequate" radio link performance refers to a bit error rate not in excess of 1.0E-3. Therefore, a base station provides adequate coverage from between 6500 square feet to 14,625 square feet, by applying a hexagonal cellular tiling factor of $2.6 \times r^2$.

4) The base station coverage outlined above incorporates an employee population of between 35 (6500/185) to 79 (14,625/185).

5) Assuming the long-term goal of 100% wireless penetration, the wireless user population within the range of a cell is between 35 and 79 persons. Studies indicate that the traffic offered in a typical office environment during peak busy hour is 0.2 Erlangs on average. Therefore, this user population will offer between 7.0 Erlangs (35 x 0.2) and 15.8 Erlangs (79 x 0.2).

6) Assuming a grade of service equivalent to a PBX (p = 0.005, where p is the probability of a blocked call), and referring to the Erlang B tables (see Appendix A), the following number of voice channels per single base station will be required:

> 7.0 Erlangs   15 channels
> 15.8 Erlangs 27 channels

Audio Bit Rate Requirements

Virtually all of the envisioned voice systems will utilize digital encoding techniques. There exists a variety of encoding techniques which may be employed, and these differ in regard to bit rate efficiency, real-time delay, algorithmic complexity, cost and power of processing, and of course audio quality. A representative list of several voice compression approaches is included in Appendix B.

Many current digital cordless telecommunications standards have adopted 32 Kbps Adaptive Differential Pulse Code Modulation (ADPCM), including Digital European Cordless Telecommunications (DECT), Second Generation Cordless Telephone (CT-2), and Japan Personal Handiphone (PHP). This format is based on a CCITT G.721 specification for speech encoding, and it has been the method of choice for several reasons:

1. Subjective voice quality is considered to be "Toll" quality

2. It is reasonably efficient in bit requirements

3. Low absolute delay eliminates the need for echo cancellation

4. It has a low cost of implementation

5. It consumes low power, suitable for small portable devices

6. There is low degradation with tandem encodings

7. It is robust under random bit errors

Undoubtedly there will emerge a methodology which is acceptable along all the important parameters but which requires a bit rate closer to 16 Kbps, but for the near future 32 Kbps appears to be the appropriate choice and this is the figure included in this spectrum requirement analysis.

System Bit Overhead and Modulation Format

All real systems require an effective bit rate higher than that needed for the audio alone. There is time required for duplex turnaround and there are additional bits required for command and control, call setup, collateral data, and error control.

The amount of overhead burden depends significantly upon system architecture, method of multiple access, and amount of collateral data. Achievable system bit rate overhead ranges from 4 kbps to over 16 kbps, depending on call setup and supervision requirements. As more advanced voice compression techniques, such as 16 kbps ADPCM, become feasible, this overhead bit rate is unlikely to diminish.

In addition to the gross bit rate for a system, the modulation format employed also plays a role in determining the overall spectrum requirements. The choices are many and the tradeoffs must be made between spectrum efficiency, error rate profiles, and implementation costs. Gaussian Minimum Shift Keying (GMSK) is but one implementation choice, but is a representative one reflecting wide acceptance and a reasonable balance of costs and performance.

With GMSK, the first spectral null occurs at 0.75 times the bit rate, and it is thus often convenient to separate the transmission channels by 1.5 times the bit rate. Other practical modulation formats may achieve slightly greater spectral efficiency but would involve differing assumptions for errors and cost.

The following table lists several specified systems and their total spectrum needs per conversation channel. These figures, of course, bundle in the bit rate requirement, system overhead, and modulation format spectrum efficiency.

System	Channels/Carrier	Carrier Bandwidth	Effective Bandwidth/Channel
DECT	12 Channels	1.728 MHz	144 kHz/channel
CT-2	1 Channel	100 kHz	100 kHz/channel
PHP	4 Channels	300 kHz	75 kHz/channel
FA1318	10 Channels	700-800 kHz	70-80 kHz/channel

The 100 kHz per channel required by CT-2 is a reasonable nominal figure to use for the analysis. It is relatively efficient among extant technologies, and since CT-2 carries little collateral data this figure becomes somewhat aggressive for future systems, setting a precedent to improve efficiencies over time.

Spectrum Requirement for a Single Cell

If the results from the above three analyses are combined, a single cell will require from between 1.5 MHz (15 x 100 kHz) to 2.7 MHz (27 x 100 kHz) of spectrum in order to adequately serve the user population within its coverage area.

This range of spectrum utilization stems from the absolute coverage area of a single base station in various interior environments; some environments have better radio frequency propagation characteristics than others, and hence the coverage area is greater for that case. A greater coverage area mandates a greater amount of spectrum in order to deliver more voice channels.

Propagation Issues

Clearly, although about 1.5 MHz to 2.7 MHz of spectrum is required to serve a representative user population in an "isolated situation", substantially more spectrum is required to address that same user density which extends for considerable distance in all directions. Cellular radio technology recognizes this "spatial factor" in its "frequency reuse patterns" by placing considerable distance between zones (or "cells") which share the same operating frequency. The multiplicity of frequencies needed to serve a large space without reusing a given frequency is called the reuse factor. The amount of spatial separation between co-frequency cells is dictated by propagation issues and the radios' tolerance to interfering signals, and that distance governs the reuse factor.

Some writings have suggested a reuse factor of about 25 to be generally adequate. Assumptions which influence such computations include whether interference from only the first "tier" of interferers and not subsequent, or higher, tiers is included, and also whether a propagation law of third order (inverse third-root) or fourth order (inverse fourth-root) is taken into consideration. Experience has now shown that situations experiencing propagation laws closer to second or third order mandate a substantially higher reuse factor.

The three-dimensional aspect of indoor PCS applications may further increase the reuse factors. While this consideration is not important for vehicular cellular telephone, it is a very real part of the scenario for wireless PBX systems in multi-story building complexes. Imperfect isolation between

floors in such buildings, and also interference from nearby buildings, present potent and complex interference issues for such systems, again dictating a large reuse factor to afford adequate separation between co-frequency cells. Published studies have discussed vertical reuse factors in the range between three to six. A vertical reuse pattern size of three takes into account the floor above and below in a multi-story environment.

Another practical consideration for emerging PCS applications, principally for indoor wireless communications, is the non-homogenous nature of indoor propagation. The diversity of interior structures, reflectors, absorbers, and so forth, leads to situations where propagation factors differ in various directions (See Appendix C). This leads to numerous instances in which propagation from an interferer may follow an advantageous path relative to that of the intended signal, again a mechanism which is mitigated by a higher reuse factor.

Frequency Reuse Factor

A suitable reuse factor pattern size necessary to achieve a minimally acceptable level of performance varies widely with the specific situation. This analysis is based on an average signal-to-interference ratio of 20 dB, which is required to maintain a minimum fade margin of 10 dB in a multipath environment.

The empirical results obtained by the contributing members of this paper conclude that indoor transmission is generally characterized by third order (inverse third-root) propagation. Fourth order propagation, though it has been observed in some exceptional situations, is not a common occurrence for the microcell sizes considered in this document.

Appendix D presents frequency reuse pattern sizes based on the work of D.C. Cox and others. It takes into consideration both the case of first tier interferers only, that is, only the effects of immediately adjacent interfering cells, as well as higher tier interferers which include all interferers within a geographic area.

The first page of Appendix D presents a two dimensional model, while the second page presents the reuse pattern sizes for a three-dimensional model. The three dimensional model assumes a vertical reuse pattern size of N=3, as stated earlier in this paper. N=3 is proposed since it is the minimum practical reuse value that can be used, as through-floor penetration is a realistic effect observed with in-building transmission at the frequencies proposed for Unlicensed PCS.

Therefore, assuming a three-dimensional model for an in-building wireless system, for a signal-to-interference ratio of 20 dB, and a third order propagation (n=3) scenario, a minimum frequency reuse pattern size of 71.1 results for a first tier interference assumption. For a higher tier interference assumption, the minimum frequency reuse pattern size corresponds to 99.0.

Systems employing dynamic channel selection can achieve an improvement in the frequency reuse factor pattern. An ETSI study (ETR-42) of DECT systems using a "Least Interfered Channel" selection criterion suggests that an improvement on the order of three or more is feasible. This can offset much of the degrading effects of the lower propagation exponent that will typify many indoor environments. Applying this factor of 3 to the above assumptions yields a frequency reuse pattern size of 23.7 (71.1/3) for the first tier of interferers, and a reuse factor of 33 (99.0/3) for higher tier interferers.

The conclusion of this section is that the minimum frequency reuse pattern size for an in-building wireless system ranges from between 23.7 (or 24) to 33.

Total System Spectrum Requirements

The total spectrum requirements for a wireless PBX system can be determined as follows:

1) Base Station call capacity (as determined from Erlang B)

    7 Erlangs = 15 channels, minimum
    15.8 Erlangs = 27 channels, maximum

2) Single Base Station (Cell) spectrum requirements

    $f_c = n \times f_{ch}$, where n = cell channels and f_{ch} = effective bandwidth per channel

    15 x 100 kHz = 1.5 MHz, minimum
    27 x 100 kHz = 2.7 MHz, maximum

3) Total System (Multi-Cell) spectrum requirements

    $f_S = N \times f_c$, where N = frequency reuse pattern size and f_c = single cell bandwidth

    N = 24 (First Tier of Interferers Only)

    24 x 1.5 = 36.0 MHz, minimum
    24 x 2.7 = 64.8 MHz, maximum

    N = 33 (Higher Tier of Interferers Considered)

    33 x 1.5 = 49.5 MHz, minimum
    33 x 2.7 = 89.1 MHz, maximum

Conclusion

Wireless PBX systems designed to provide primary service will require sufficient spectrum in order to afford the quality of service needed for universal acceptance and economic success. The specific spectrum required is highly dependent on the application and the influence of other systems sharing the same frequency band.

The first frequency reuse pattern size example takes into account the most optimistic and perhaps unrealistic view of the first tier interference scenario, with a third order propagation exponent. This yields a reuse pattern of 24, with a resulting spectrum requirement of between 36 to 65 MHz.

A more realistic view considers higher tier interferers, again with a third order propagation exponent. The derived reuse pattern is 33, with a resulting spectrum requirement of between 50 to 89 MHz.

Therefore, it is concluded that any spectrum allocation less than 40 MHz may exclude a substantial number of viable applications, or would require a reduction in cell size to the extent that economic justification is significantly compromised.

APPENDIX A

Erlang B Traffic Tables

TABLE 1

Design Table for Loss System

Lost Calls Cleared
Infinite Number of Traffic Sources
Full Availability

Selective Parameters

N = Number of Servers
P = Probability of Loss

Table Values

A = Offered Load in Erlang

Formula

Erlang B

N	.0001	.0002	.0003	.0005	.001	.002
1	.001	.001	.001	.001	.001	.002
2	.015	.021	.025	.033	.046	.066
3	.087	.111	.127	.152	.194	.249
4	.235	.283	.316	.363	.440	.536
5	.452	.527	.578	.649	.763	.900
6	.729	.832	.900	.996	1.146	1.326
7	1.055	1.186	1.273	1.393	1.579	1.799
8	1.422	1.582	1.686	1.830	2.052	2.311
9	1.826	2.014	2.135	2.302	2.558	2.855
10	2.261	2.475	2.614	2.803	3.093	3.427
11	2.722	2.963	3.118	3.330	3.652	4.022
12	3.207	3.475	3.646	3.879	4.232	4.637
13	3.714	4.006	4.193	4.447	4.831	5.271
14	4.239	4.556	4.758	5.033	5.447	5.920
15	4.782	5.123	5.340	5.634	6.078	6.583
16	5.339	5.704	5.936	6.250	6.722	7.259
17	5.911	6.300	6.546	6.879	7.379	7.946
18	6.496	6.907	7.167	7.519	8.046	8.644
19	7.093	7.526	7.800	8.170	8.724	9.352
20	7.701	8.156	8.443	8.831	9.412	10.07
21	8.319	8.795	9.096	9.502	10.11	10.79
22	8.947	9.444	9.758	10.18	10.81	11.53
23	9.583	10.10	10.43	10.69	11.53	12.27
24	10.23	10.77	11.11	11.56	12.24	13.01
25	10.88	11.44	11.79	12.26	12.97	13.76
26	11.54	12.12	12.48	12.97	13.70	14.52
27	12.21	12.81	13.18	13.69	14.44	15.29
28	12.88	13.50	13.89	14.41	15.18	16.06
29	13.56	14.20	14.60	15.13	15.93	16.83
30	14.25	14.90	15.31	15.86	16.68	17.61
31	14.94	15.61	16.03	16.60	17.44	18.39
32	15.63	16.33	16.76	17.34	18.21	19.18
33	16.34	17.04	17.49	18.09	18.97	19.97
34	17.04	17.77	18.22	18.84	19.74	20.76
35	17.75	18.50	18.96	19.59	20.52	21.56

N	.003	.005	.01	.02	.03	.05
1	.003	.005	.011	.021	.031	.053
2	.081	.106	.153	.224	.282	.382
3	.289	.349	.456	.603	.716	.900
4	.602	.702	.870	1.093	1.259	1.525
5	.995	1.132	1.361	1.658	1.876	2.219
6	1.447	1.622	1.909	2.276	2.543	2.961
7	1.947	2.158	2.501	2.936	3.250	3.738
8	2.484	2.730	3.128	3.627	3.987	4.543
9	3.053	3.333	3.783	4.345	4.748	5.371
10	3.648	3.961	4.462	5.084	5.530	6.216
11	4.267	4.611	5.160	5.842	6.328	7.077
12	4.904	5.279	5.876	6.615	7.141	7.950
13	5.559	5.964	6.608	7.402	7.967	8.835
14	6.229	6.664	7.352	8.201	8.804	9.730
15	6.913	7.376	8.108	9.010	9.650	10.63
16	7.610	8.100	8.875	9.829	10.51	11.54
17	8.317	8.834	9.652	10.66	11.37	12.46
18	9.034	9.578	10.44	11.49	12.24	13.39
19	9.761	10.33	11.23	12.33	13.12	14.32
20	10.50	11.09	12.03	13.18	14.00	15.25
21	11.24	11.86	12.84	14.04	14.89	16.19
22	11.99	12.64	13.65	14.90	15.78	17.13
23	12.75	13.42	14.47	15.76	16.68	18.08
24	13.51	14.20	15.30	16.63	17.58	19.03
25	14.28	15.00	16.13	17.51	18.48	19.99
26	15.06	15.80	16.96	18.38	19.39	20.94
27	15.84	16.60	17.80	19.27	20.31	21.90
28	16.62	17.41	18.64	20.15	21.22	22.87
29	17.41	18.22	19.49	21.04	22.14	23.83
30	18.20	19.03	20.34	21.93	23.06	24.80
31	19.00	19.85	21.19	22.83	23.99	25.77
32	19.81	20.68	22.05	23.73	24.92	26.75
33	20.61	21.51	22.91	24.63	25.85	27.72
34	21.42	22.34	23.77	25.53	26.78	28.70
35	22.23	23.17	24.64	26.44	27.71	29.68

APPENDIX B

<u>Voice Compression Algorithm Comparison</u>

MOS	RATING	QUALITY GRADE
5	Excellent	Broadcast
4	Good	Toll
3	Fair	Communication
2	Poor	Synthetic
1	Bad	

Voice Compression Algorithm Comparison

ALGORITHM	DATA RATE	MOS	MIPS	ECHO CONTROL
Log PCM	64 Kbps	4.3	NA	No
ADPCM	32 Kbps	4.1	6	No
CVSD	32 Kbps	3.4	NA	No
ADPCM	24 Kbps	3.5	6	No
LD-CELP	16 Kbps	4.0	20	No
VAPC	16 Kbps	3.5	10	Yes
Subband	16 Kbps	3.2	5	No
ATC	16 Kbps	3.7	8	Yes
ADPCM	16 Kbps	2.5	6	No
CVSD	16 Kbps	2.2	NA	No
RPE-LPC	13 Kbps	3.5	5	Yes
RELP	13 Kbps	3.5	5	Yes
SEV	9.6 Kbps	3.7	20	Yes
VSELP	8 Kbps	3.7	20	Yes
CELP	8 Kbps	3.7	20	Yes
CELP	4.8 Kbps	3.0	15	Yes
LPC-10	2.4 Kbps	2.5	5	Yes

APPENDIX C

In-Building Propagation Analysis

IN-BUILDING PROPAGATION ENVIRONMENT
AND UNLICENSED PCS ETIQUETTE

Anatoly Tsaliovich
AT&T Bell Laboratories

When evaluating the propagation specifics for unlicensed PCS, the emphasis is made on the in-building environment. This can be justified by the anticipated applications, as well as by the potentially higher indoor user density.

An in-building environment presents a multipath channel generated by fixed and randomly moving signal reflectors and scatterers. If a signal $s(t)$ is transmitted in such channel, the received signal may be expressed as

$$r(t) = \sum_n \alpha_n(t) s[t - \tau_n(t)], \qquad (1)$$

where $\alpha_n(t)$ and $\tau_n(t)$ are the attenuation and the propagation delay for the signal received on the nth path.

Statistically, such multipath propagation can be modelled by a Ricean-distributed random variable

$$R = \sqrt{\sum_{i=0}^{n} X_i^2}$$

with a pdf:

$$p_R(r) = \frac{r^{n/2}}{\sigma^2 s^{(n-2)/2}} e^{-(r^2+s^2)/2\sigma^2} I_{n/2-1}\left(\frac{rs}{\sigma^2}\right) \qquad (2)$$

Presently, numerous simplified models are utilized to evaluate the in-building environment. As an example, several of them are presented in the Table 1. These and other models emphasize different factors, depending on specific applications. However, for rough estimates of relative performance within indoor environment even simpler models may be useful. Such factors as Doppler effect, delay spread, Rayleigh (random, with zero second central moment distribution) fading and some others, can often either be disregarded or easily accounted for. Then, to obtain useful practical results it may be sufficient to account only for the mean power loss and slow signal shadowing statistics.

Consider first a transmit antenna in free space, radiating power P_T, W at a frequency f, GHz. The power at the LOS receive antenna located at a separation distance r (in m) from the transmit antenna, can be expressed as

$$P_R = P_T G_T G_R \frac{Q}{f^2} r^{-\alpha} \qquad (3)$$

where G_T and G_R - are the transmit and receive antenna gains, respectively; Q - is a constant ($Q \approx 6 \times 10^{-4}$).

Exponent α determines the mean propagation path loss. In free space environment $\alpha = 2$.

In the simplest case, for in-building environment similar propagation models can be adopted as for free space, but with different propagation loss exponents:

$$P_R = P_T G_T G_R D \frac{Q}{f^2} r^{-\alpha} \tag{4}$$

Depending on the building construction materials, floor plans, and microcell design, in the in-building environment typical values of α vary from 1.8 to 4.

In (4), coefficient D accounts for the positive effect of diversity techniques utilized in multi-path channels: 4 - 12 dB improvement in C/I performance.

Consider now the relative change in the receive signal level, due *only* to the change in the propagation constant exponent α. The expression (4) can then be presented as

$$P_{Rp} = \frac{A_p}{f^2} r^{-\alpha}. \tag{5}$$

In Fig. 1, the receive signal variations with the change of separation distance r are presented as a function of the propagation loss exponent, relative to some fixed level A_p/f^2.
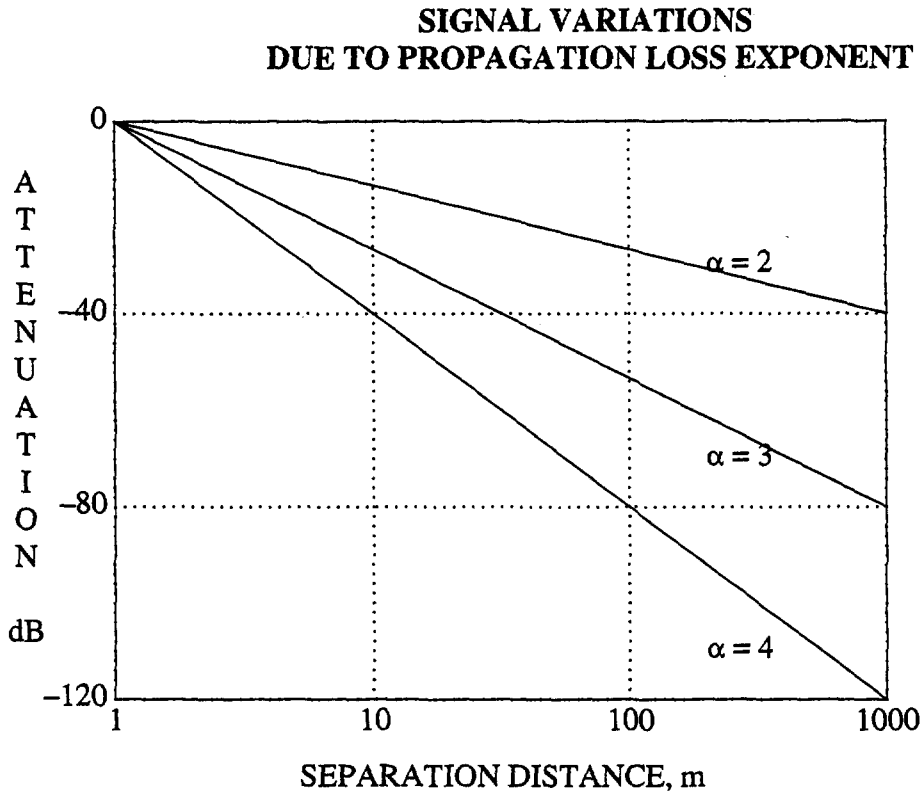
SIGNAL VARIATIONS
DUE TO PROPAGATION LOSS EXPONENT

Fig. 1

As shown, even in case of a modest 100 m cell radius, we can expect variations in the receive signal level over 40 dB **at the same separation distance between the receiver and transmitter.**

These variations will be **atop** of the regular signal level variations with the change of separation distance between the receiver and transmitter. An obvious problem with such variations is an increased potential for the receiver front end overload, or excessive loss in the channel. Even more important, that potential signal variations will result in **variable cell sites** in different installations and consequently in **different frequency re-use factors as well as different needs for spectrum.**

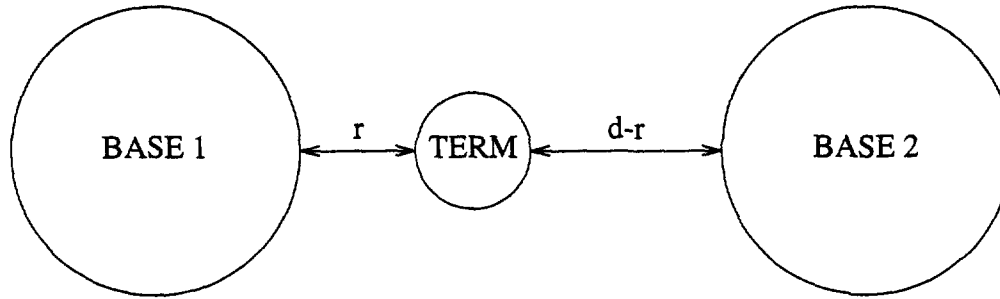Consider two base stations and a terminal (Fig. 2).

Fig. 2

As shown, the terminal receives the signal from the station 1, while the interference comes from station 2. If the mean propagation loss exponent α is the same for the signal and interference, then

$$\frac{C}{I} = (\frac{d-r}{r})^{\alpha} \tag{6}$$

and the re-use distance as a function of $T = 10lg \mid C/I \mid$ (in dB) is

$$\frac{d}{r} = 10^{\frac{T}{10\alpha}} + 1 \tag{7}$$

If for instance the required interference immunity T is assumed equal 20 dB, then with the α changing from 2 to 4, the d/r variations will be from 11 to 4.3.

The equation (7) implies a circular, or otherwise symmetrical cell. However, in the indoor environment this is as a rule not the case, because the α values in different directions (and it's a 3-D problem) may often be different. The cells cannot any more be represented by circles or any symmetrical figures, for that matter. The consequences of this can indeed be extremely dramatic.

In the worse case, the value of α should be considered $\alpha_s = 4$ for the signal and $\alpha_i = 2$ - for the interference. Then, it can be shown (I can provide the derivation, if necessary):

$$\frac{d}{r} = 10^{\frac{T}{10\alpha_i}} r^{\frac{\alpha_s}{\alpha_i}-1} + 1 \tag{8}$$

Substituting $\alpha_s = 4$, $\alpha_i = 2$, and $T = 20$, obtain

$$d/r = 10r + 1 \qquad\qquad (9)$$

Thus, in this particular case, the spacing d between the base stations is proportional to the square of the cell radius (instead of a direct proportionality in the symmetrical loss factors). In a 3-D case, the situation is even worse. It is easy to see, that the asymmetry in the propagation conditions within the in-building environment, makes the re-use distance much larger, and practically the re-use may often be impossible alltogether.

CONCLUSIONS

While the adopted assumptions are extremely pessimistic, nevertheless the obtained results indicate the potential for serious problems. Partially, these problems can be alleviated by utilizing adaptive power control. However, even this measure may not be sufficient. Then, the only possible solution can be in providing "orthogonal" allocations to different cells, resulting in the increase of the number of the necessary channels. This can be achieved by larger frequency allocations, by time sharing, or both.

The worst case scenario per expression (9), exists in case of interference *between different systems*. There, the synchronization between the interfering channels is problematic, making the time sharing difficult. In this case, the LBT principle may provide the necessary protection (although at a cost!), and should be maintained.

On the other hand, for a particular case of co-channel inteference *within the same system*, the interfering channel can be relatively easy identified and synchronized with. In this case, a combination of the LIC rules with some kind of time sharing will solve the problem.

Table 1

IN-BUILDING PROPAGATION MODELS

AUTHOR(S) COMMENTS	FEATURES	EQUATION
A. Saleh and R. Valenzuela	Statistical model: pulse-modulated CW channel	$E_\theta[\,\lvert y(t) \rvert^2] = \sum_k \beta^2_k \; p^2(t - \tau_k)$
R. Bultitude	Random variation of CW signal Mean signal model	$D^{-1.8}$ mean receive power law with Ricean distribution having K=-6 to -12 dB
J. Keenan and A. Motley	Lognormal mean signal model	$P_{R(Raileigh)} = P_T - L_{lgnvar-clutter} - 10n \log_{10}D + kf + pw$
T. Rappaport	Statistical channel impulse response model. Open building plan.	$A_k(T_k, S_m, D_n)(dB \; below \; 10\lambda \; ref) = 10 \times n\,(T_K, S_m) \times \log(\frac{D_n}{2.3})$
K. Blackard	Corner diffraction (d_0) exponent. No LOS propagation and direct penetration through the low loss obstacles	$L_p(r) = (\frac{\lambda}{4\pi r})^2$, if $r < r_0$ $L_p(r) = (\frac{\lambda}{4\pi r_0})^2 (\frac{r_0}{r})^\alpha$, if $r \geq r_0$
D.Cox/W.Jakes	Small scale&large scale variations. Suburban residence	$y_c(z,t) = L(z)R(z)e^{j\omega t + j\phi(z,t)}$

APPENDIX D

Frequency Reuse Pattern Size

Two Dimensions Only, Single Tier

		Minimum N	
S/I	n=2	n=3	n=4
10 dB	20	5.1	2.6
15 dB	63	11.0	4.6
20 dB	200	23.7	8.2
25 dB	632	51.0	14.5
30 dB	2000	110	25.8

Two Dimensions Only, Multi-Tier

		Minimum N	
S/I	n=2	n=3	n=4
10 dB	∞	7.1	2.8
15 dB	∞	15.3	5.0
20 dB	∞	33.0	9.0
25 dB	∞	71.0	15.9
30 dB	∞	153	28.3

Three Dimensions Only, Single Tier

		Minimum N	
S/I	n=2	n=3	n=4
10 dB	60	15.3	7.8
15 dB	189	33.0	13.8
20 dB	600	71.1	24.6
25 dB	1896	153	43.5
30 dB	6000	459	77.4

Three Dimensions Only, Multi-Tier

		Minimum N	
S/I	n=2	n=3	n=4
10 dB	∞	21.3	8.4
15 dB	∞	45.9	15.0
20 dB	∞	99.0	27.0
25 dB	∞	213	47.7
30 dB	∞	459	84.9

FREQUENCY REUSE PATTERN SIZE

Given an infinite set of hexagonal patterns, the signal to interference ratio (S/I) can be approximated by the following formula[1].

$$S/I \approx (3\beta)^n / 6 \sum_{t=1}^{\infty} (1/t^{n-1})$$

where: β = a channel reuse parameter
           n = distance dependent propagation exponent

Also,

$\beta = D/3r$

where: D = reuse distance
           r = cell radius

Since $D/r = (3N)^{1/2}$ where N = number of cells in reuse pattern

$$S/I \approx (3N)^{n/2} / 6 \sum_{t=1}^{\infty} (1/t^{n-1})$$

Solving for N,

$$N \approx 1/3 \left((S/I) \ 6 \sum_{t=1}^{\infty} (1/t^{n-1}) \right)^{2/n}$$

The expression $\sum_{t=1}^{\infty} (1/t^{n-1})$ is the Riemann Zeta Function which can be evaluated via tables[2]. For propagation exponents of n = 2, 3, and 4, the value of the function is:

n	$\sum_{t=1}^{\infty} (1/t^{n-1})$
2	∞
3	1.64493
4	1.20206

Based on the foregoing, the minimum reuse pattern size may be evaluated for propagation exponents of 2, 3, and 4 and S/I yielding:

| S/I | Minimum N | | |
	n=2	n=3	n=4
10 dB	∞	7.1	2.8
15 dB	∞	15.3	5.0
20 dB	∞	33	9.0
25 dB	∞	71	15.9
30 dB	∞	153	28.3

The higher tier interferers may not be significant in some environments. For example, a particular building construction may provide high attenuation of interferers outside the building. For perspective on a close to best case scenario, consider the case where only the first tier interferers are present; i.e., t=1. For this case the term $(1/t^{n-1})$ always takes on the value 1. The minimum reuse pattern size for propagation exponents of 2, 3, and 4 and S/I with only first tier interferers is as follows:

| S/I | Minimum N | | |
	n=2	n=3	n=4
10 dB	20	5.1	2.6
15 dB	63	11.0	4.6
20 dB	200	23.7	8.2
25 dB	632	51	14.5
30 dB	2000	110	25.8

Note that S/I represents the static signal to interference ratio achievable under the given reuse scenario. Margin for variations such as shadowing and fading must be explicitly factored into S/I to arrive at the required static S/I.

1 D.C. Cox, "Co-channel interference considerations in frequency reuse small-coverage area radio systems," IEEE Trans. Commun., vol COM-30, pp. 135-142, Jan. 1982.

2. CRC Standard Mathematical Tables, The Chemical Rubber Co., 1968.